

Probing of Wtb Anomalous Couplings via the tW Channel of Single Top Production

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Abstract

The potential of LHC for investigation of the W - t - b vertex through the tW channel of single top quark production is studied. Unlike the other two single top quark production processes (t -channel and s -channel), the tW channel provides the possibility to study the Wtb vertex without receiving contamination from FCNC. This study has been done at parton level but is involved the separation of signal from backgrounds when both W -bosons decay to leptons. In this study \mathcal{CP} is assumed to be conserved. The 68% C.L. bounds on the non-Standard Model couplings are estimated.

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1 Introduction

One of the main goals of the upcoming operational LHC is to search for new physics beyond the Standard Model (SM). Because of the large mass of the top quark among all observed particles within the SM, it may give a special role in the generation of masses. Therefore, it is crucial that its interactions with other particles be studied carefully. The deviations of the top quark interactions from the SM predictions may represent a good way to learn more about the nature of the electroweak symmetry breaking [1],[2].

One approach to describe possible new physics effects is to use a model independent technique based on the effective low energy Lagrangian. In this approach, the SM Lagrangian is modified by adding new $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ gauge invariant operators [3],[4]:

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2} \sum_i C_i \mathcal{O}_i. \quad (1)$$

where \mathcal{L}_{SM} is the SM Lagrangian, Λ is the new physics scale, \mathcal{O}_i are dimension six operators which are gauge invariant before electroweak gauge symmetry breaking. C_i are constants which represent the coupling strengths of \mathcal{O}_i . The dimension five operators violate the lepton number conservation.

Upon electroweak symmetry breaking and giving our attention to the top quark, the modified Wtb couplings can be expressed as [4]:

$$\Gamma_{Wtb}^\mu = -\frac{g}{\sqrt{2}} [\gamma^\mu (F_{L1} P_L + F_{R1} P_R) - \frac{i\sigma^{\mu\nu} q_\nu}{m_W} (F_{L2} P_L + F_{R2} P_R)] + (h.c.) \quad (2)$$

where g is the weak coupling constant, m_W is the W-boson mass, q_ν is the W-boson four-momentum. $P_{R,L} = \frac{1 \pm \gamma_5}{2}$ is the right-handed (left handed) projection operator. Assuming \mathcal{CP} conservation, $F_{L1,2}$ and $F_{R1,2}$ are real form factors. These anomalous couplings are related to the coefficients $C_{tW\Phi}$ and $C_{bW\Phi}$ in the general effective Lagrangian by [4]:

$$F_{L2} = \frac{C_{tW\Phi} \sqrt{2} m_W v}{g \Lambda^2} \quad , \quad F_{R2} = \frac{C_{bW\Phi} \sqrt{2} m_W v}{g \Lambda^2} \quad (3)$$

where Λ is the scale of new physics. At tree level of the SM, $F_{L1} = V_{tb} \simeq 1$ and $F_{R1} = F_{L2} = F_{R2} = 0$.

At hadron colliders, top quarks can be produced in $t\bar{t}$ pairs via strong interactions and singly via electroweak interactions. The introduced anomalous couplings have been studied via top pair events at the LHC and Tevatron in [5],[6],[7].

In the SM single top quark events are expected to be produced via the t -channel process ($bq \rightarrow q't$), the s -channel process ($q\bar{q}' \rightarrow t\bar{b}$) and the tW -channel process ($gb \rightarrow tW^-$). These three processes have completely different kinematics and can be observed separately [1]. The first evidence for single top was reported by D0 experiment at Tevatron [8]. At the Tevatron, the events of the tW -channel can not be observed because of the very small cross section of this process.

A complete study of the Wtb anomalous couplings using the t -channel and the s -channel for LHC and Tevatron has been performed in [9] which has given the following bounds on the anomalous couplings (assuming 10% systematic uncertainty):

$$-0.094 \leq F_{L2} \leq 0.34 \quad , \quad -0.17 \leq F_{R2} \leq 0.18 \quad (4)$$

The data coming from $b \rightarrow s\gamma$ has applied very tight constraints on the F_{R1} [10]. Thus we do not consider F_{R1} in the present study.

The tW -channel has almost a large cross section at the LHC (~ 60 pb) and does not receive any contribution from FCNC (Flavor Changing Neutral Current), therefore it can be used to study the vertex of W - t - b . The aim of this article is to investigate the sensitivity of this channel to anomalous couplings and estimation of the possible bounds on F_{R2} and F_{L2} .

2 The Top Quark Width Sensitivity to the Anomalous Couplings

The Standard Model predicts the top quark lifetime to be around 4×10^{-25} s which corresponds to the top quark width of 1.5 GeV. One should note that because of the experimental restrictions, it is very difficult to measure this very short lifetime or the corresponding width. However, we are able to set a lower limit on the top quark width from the available data from Tevatron. In [11] an upper limit has been set on the top quark width using a likelihood

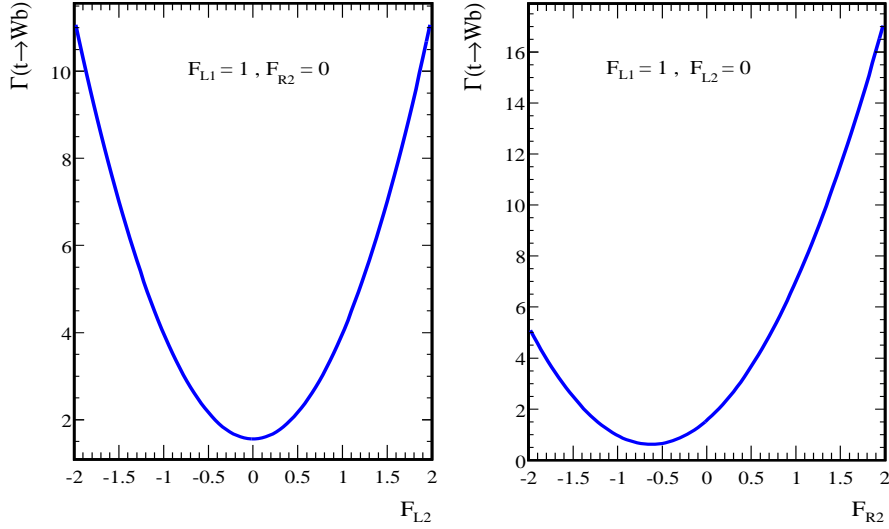


Figure 1: The tree level width of the top quark (in GeV) in terms of anomalous couplings

fit to the reconstructed top mass distribution. In the analysis the lepton+jets channel of $t\bar{t}$ candidates, in which one of two W-bosons decays to $l\nu_l$ while the other decays to qq' , is used to reconstruct the top quark mass. Finally, the estimated upper bound on the top quark width is 12.7 GeV with 95% C.L. This is corresponding to the lower limit of 5.2×10^{-26} s for the top quark lifetime. The top quark width will not be measured very precisely at the LHC [15].

From another side, the introduced Wtb coupling, at tree level and in the limit of $m_b \rightarrow 0$, leads to the following formula for the width of top quark [12],[13]:

$$\Gamma_{t \rightarrow Wb} = \frac{G_f m_t m_W^2}{8\sqrt{2}\pi} \frac{(r^2 - 1)^2}{r^4} [(r^2 + 2)(F_{L1}^2 + F_{R1}^2) + (2r^2 + 1)(F_{L2}^2 + F_{R2}^2) + 6r(F_{L1}F_{R2} + F_{R1}F_{L2})] \quad (5)$$

where, m_t and m_W are top mass and W-boson mass, respectively and $r = \frac{m_t}{m_W}$. Fig.1 shows the top quark width as a function of anomalous couplings (F_{L2}, F_{R2}) at tree level.

Obviously, the top quark width varies around 10-15 GeV when the anomalous couplings change in a wide region $(-2.0, 2.0)$. As stated above, the upper limit on the top quark width

from the reconstructed top quark invariant mass distribution at Tevatron is around 12.7 GeV. This means that a wide region of the anomalous couplings (F_{L2}, F_{R2}) is allowed from the present top quark invariant mass measurement.

In the next section the sensitivity of the cross section of the tW channel single top to the anomalous couplings is examined and new bounds on the anomalous couplings are estimated.

3 The tW Channel Cross Section Sensitivity to the Anomalous Couplings

The dependency of the tW channel of single top quark cross section on the anomalous couplings at the LHC is presented in Fig.2. This figure has been obtained by using the CompHEP package [14]. In calculation of the cross section, it is assumed that $m_{top} = 175$ GeV/c², $m_b = 4.8$ GeV/c² and CTEQ6L1 is used as the proton parton distribution function.

According to CMS Collaboration full simulation results, the relative statistical uncertainty on measurement of the cross section ($\frac{\Delta\sigma}{\sigma}$) of the tW channel taking into account 10 fb⁻¹ of integrated luminosity is 9.9% [15]. While ATLAS collaboration predicted 3% for this value with 30 fb⁻¹ of integrated luminosity of data [16]. Therefore, the cross section of the tW channel will be measured precisely when the LHC is operational.

In the tW channel process the single top quark is produced via $gb \rightarrow tW^-$ process. In the di-leptonic decay mode, besides the charged lepton coming from top quark, missing energy and b-jet, the final state contains another charged lepton (from the real W^- -boson) with opposite sign of the charged lepton coming from top quark. The distribution of the transverse momentum ($p_T = \sqrt{p_x^2 + p_y^2}$) of the charged lepton and the b-quark from the top quark decay are shown in Fig.3. According to the left plot in Fig.3, the transverse momentum of the b-quark from the top quark is insensitive to the anomalous couplings. In contrast, the transverse momentum distribution of the charged lepton is shifted in the presence of anomalous couplings with respect to the SM case. As it has been shown in the right plot in Fig.3, the mean value of the transverse momentum of the charged lepton is shifted toward the large p_T region around 6 GeV when the anomalous couplings are $F_{L2} = F_{R2} = 0.2$. One

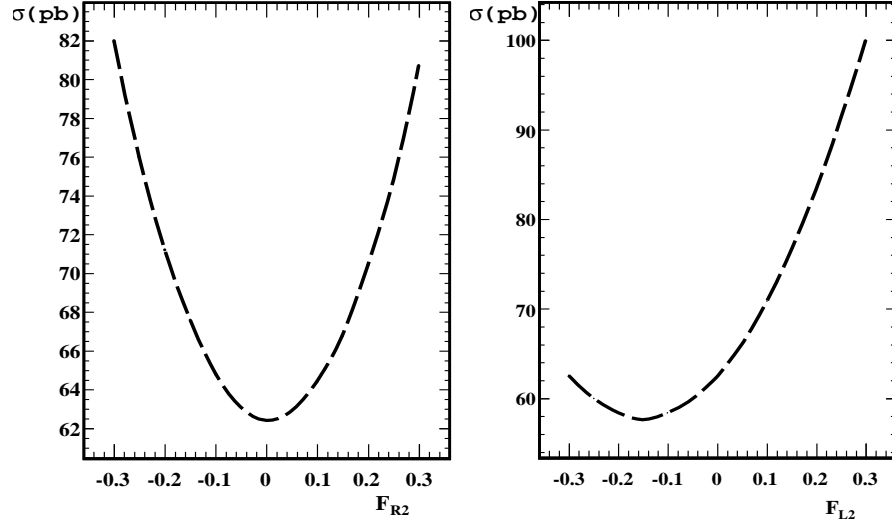


Figure 2: The dependency of the tW channel single top production cross section on F_{R2} when $F_{L1} = 1$, $F_{L2} = 0$ (left plot) and on F_{L2} when $F_{L1} = 1$, $F_{R2} = 0$ (right plot).

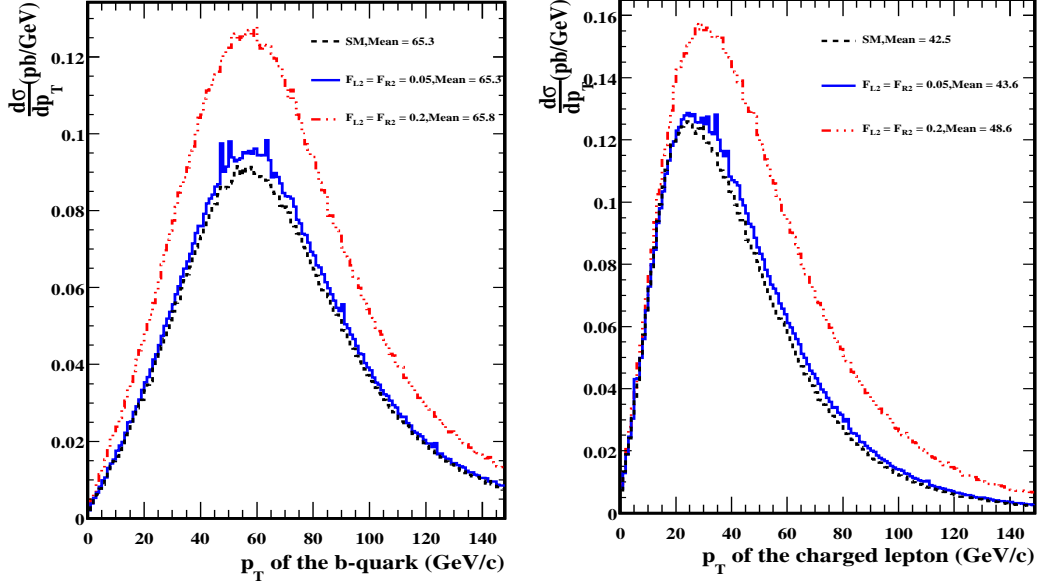


Figure 3: The transverse momentum distributions of the charged lepton and b-quark coming from top in the tW channel single top in the SM and for different values of F_{L2} , F_{R2} .

should note that this mean value depends on the range of the histogram (e.g. the mean value of the p_T distribution is increased when the range of the histogram is set to 300 GeV/c instead of 150 GeV/c). According to the charged lepton p_T distribution, for very small values of F_{L2} , F_{R2} , the shift toward large p_T region is negligible.

Modern detectors at the LHC are able to measure the transverse momentum of the charged leptons (muon and electron) very precisely. For example, the CMS detector is able to measure the p_T of muons with the precision of 1.5% (when muon is in the central region of the detector and $p_T \lesssim 100$ GeV/c) [17]. Therefore, a shift of around 6 GeV might be observable which corresponds to $F_{L2} = F_{R2} = 0.2$. However, a shift in the p_T of the charged lepton distribution corresponding to $F_{L2} = F_{R2} = 0.05$ is not observable.

In order to obtain a realistic estimate of the sensitivity of the tW channel single top at the LHC, one has to take into account backgrounds, detector effects and selection cuts. Obviously, a comprehensive analysis of all reducible backgrounds and detector effects is beyond the scope of this study and must eventually be performed by the experimental collaborations. In [18] a Monte Carlo study at parton level has been performed which is involved the separation of signal from backgrounds when two W-bosons decay to leptons. The most contributing backgrounds are $t\bar{t}$ and W^+W^-b . The signal contains two high p_T charged leptons, only one jet (the b-jet coming from top quark) and missing energy.

According to the proposed strategy for separation of signal from backgrounds in [18], the charged leptons and b-jet are required to have $p_T \geq 15$ GeV and to lie in the central region of the detector with $|\eta| \leq 2.0$. The following angular separation cut is applied on charged leptons and jet:

$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} \geq 0.4. \quad (6)$$

where $\Delta\phi$ is separation in azimuthal angle and $\Delta\eta$ is the difference in pseudorapidity. After applying the above cuts, the significance at LHC with 20 fb^{-1} of integrated luminosity is seen to be 84.9. Therefore, we use this selection strategy to suppress the backgrounds.

As mentioned before in this study, the CompHEP package [14] was used to simulate the tW channel single top production with anomalous couplings. We use simple χ^2 criterion from the transverse momentum distribution of the charged lepton (coming from the top quark)

with 20 fb^{-1} of integrated luminosity to estimate the limits on anomalous Wtb couplings. The analysis is performed after application of the mentioned cuts for backgrounds suppression from [18]. The χ^2 criterion is defined as:

$$\chi^2(F_{L2}, F_{R2}) = \sum_{i=\text{bins}} \left(\frac{N_i^{\text{non-SM}} - N_i^{\text{SM}}}{\Delta_i} \right)^2 \quad (7)$$

where N_i^{SM} is the number of standard events in the i -th bin of the transverse momentum distribution of the charged lepton and $N_i^{\text{non-SM}}$ is the number events predicted by the non-standard theory in the i -th bin (in our case the theory with anomalous Wtb couplings).

In the present study, we have taken the advantage of the fact that, for small values of F_{L2} and F_{R2} , approximately the of the cross section of the tW channel in the presence of anomalous couplings is linear in F_{L2} and F_{R2} so the $N_i^{\text{non-SM}}$ can be written linearly in F_{L2} and F_{R2} too. Therefore, χ^2 criterion depends quadratically on anomalous couplings.

In Eq.7, Δ_i is defined as:

$$\Delta_i = N_i^{\text{SM}} \sqrt{\delta_{\text{stat}}^2 + \delta_{\text{syst}}^2} \quad (8)$$

where δ_{stat} is the statistical uncertainty and δ_{syst} is the term for including systematic uncertainties. Systematic uncertainties from m_{top} , parton distribution function, QCD scales, luminosity measurements and etc. are important for accurate results. However, at this stage it is difficult to give a realistic estimate of systematics. Therefore, combined systematic uncertainties of 10% and 25% are taken into account. Because of different sources of uncertainties, taking into account a combined systematic uncertainty of 25% seems to give more realistic results.

Using the χ^2 function defined by Eq.7, the 68% confidence level contours are drawn in Fig.4 assuming 10% and 25% of systematic uncertainties.

The 68% C.L. bounds on the non-SM couplings with different values of systematic uncertainties are given in Table 3. Comparing these limits with the limits which have been estimated by using the t -channel and s -channel of single top from [9] (mentioned in the introduction), clearly the tW channel is able to give better bounds on F_{R2} .

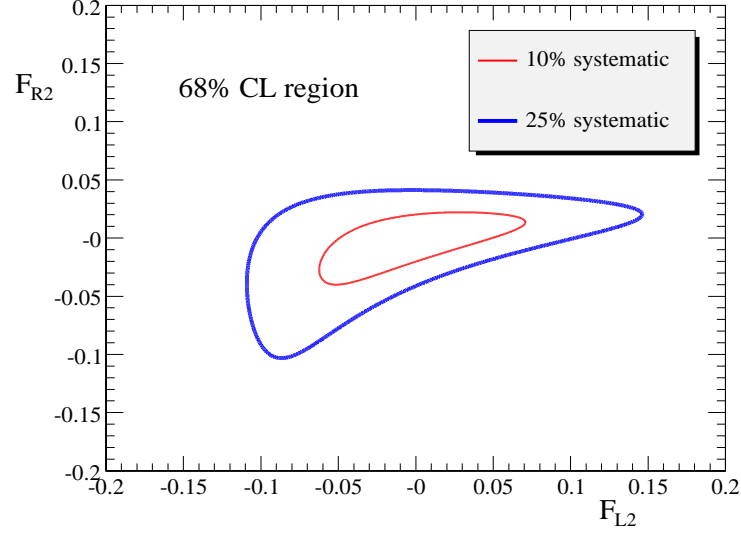


Figure 4: The 68% confidence level regions of anomalous couplings with 10% and 25% of systematic uncertainties.

Systematics	F_{L2}	F_{R2}
0%	$-0.039 \leq F_{L2} \leq 0.042$	$-0.026 \leq F_{R2} \leq 0.017$
10%	$-0.061 \leq F_{L2} \leq 0.070$	$-0.040 \leq F_{R2} \leq 0.022$
25%	$-0.11 \leq F_{L2} \leq 0.15$	$-0.105 \leq F_{R2} \leq 0.041$

Table 1: The 68% confidence level bounds on the anomalous couplings assuming different values for systematic uncertainties.

4 Conclusion

The tW channel single top quark production at LHC was considered as a probe for non-SM couplings in the top quark sector. The tW channel provides the possibility to study the Wtb vertex without receiving contamination from FCNC. The transverse momentum distribution of the b-quark from top is almost insensitive to anomalous couplings while the presence of anomalous couplings leads to a shift in transverse momentum of the charged lepton from top (toward the large transverse momentum region). Using a proposed strategy at parton level for separation of signal from backgrounds with 20 fb^{-1} of integrated luminosity of data, the 68% C.L. limits on anomalous couplings (including a combined systematic uncertainty of 25%) are found to be: $-0.11 \leq F_{L2} \leq 0.15$, $-0.105 \leq F_{R2} \leq 0.041$. Comparing with the limits estimated using the combination of t -channel and s -channel of single top quark production in [9], there is more sensitivity to F_{R2} in this channel and better bounds is obtained.

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References

- [1] M. Beneke *et al.*, hep-ph/0003033.
- [2] T. M. P. Tait, C.-P. Yuan, Phys. Rev. D63, 014018 (2000).
- [3] C. J. C. Burgess and H. J. Schnitzer, Nucl. Phys. B228, 454 (1983); W. Buchmuller and D. Wyler, Nucl. Phys. B268, 621 (1986).
- [4] K. Whisnant, J. M. Yang, B. L. Young, X. Zhang, Phys. Rev. D56, 467 (1997).
- [5] J. A. Aguilar-Saavedra, J. Carvalho, N. Castro, A. Onofre, F. Veloso, Eur. Phys. J. C50, 519 (2007).

- [6] J. A. Aguilar-Saavedra, J. Carvalho, N. Castro, A. Onofre, F. Veloso, arXiv:0705.3041 [hep-ph]
- [7] S. Tsuno, I. Nakano, R. Tanaka, Y. Sumino, Phys. Rev. D73, 054011 (2006).
- [8] D0 Collaboration, V. M. Abazov, *et al.*, Phys. Rev. Lett. 98, 181802 (2007).
- [9] E. Boos, L. Dudko, T. Ohl, Eur. Phys. J. C11, 473 (1999).
- [10] W.-M. Yao *et al.*, J. Phys. G33, 1 (2006).
- [11] CDF Collaboration, CDF note 8953, August 10, 2007.
- [12] G. L. Kane, G. A. Ladinsky, C.-P. Yuan, Phys. Rev. D45, 124 (1992).
- [13] M. Mohammadi Najafabadi, J. Phys. G34, 39 (2007).
- [14] E. Boos, V. Bunichev, M. Dubinin, L. Dudko, V. Ilyin, A. Kryukov, V. Edneral, V. Savrin, A. Semenov, A. Sherstnev, Nucl. Instrum. Meth. A534, 250 (2004).
- [15] CMS Collaboration, CMS PTDR, Vol.II, CERN/LHCC 2006-021, J. Phys. G34, 995 (2007).
- [16] ATLAS Collaboration, ATLAS PTDR, Vol.II, CERN/LHCC 1999-15.
- [17] CMS Collaboration, CMS PTDR, Vol.I, CERN/LHCC 2006-001.
- [18] T. M. P. Tait, Phys. Rev. D61, 034001 (1999).